PRECISION TETHERED FORMATIONS FOR LEO AND SPACE INTERFEROMETRY APPLICATIONS

Marco B. QUADRELLI
Enrico C. LORENZINI
Autonomy and Control Section
Jet Propulsion Laboratory – California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109-8099
marco@grover.jpl.nasa.gov

Harvard-Smithsonian Center for Astrophysics
60 Garden St., Cambridge, MA 02138
elorenzini@cfa.harvard.edu

ABSTRACT – *In this paper, we describe current research in tethered formations, and a roadmap to demonstrating the required key technologies via on-ground and in-orbit testing. A rather general model is used to predict the dynamics, control, and estimation performance of formations of spacecraft connected by tethers in LEO and deep space. These models include the orbital and tethered formation dynamics, environmental models, and models of the formation estimator/controller/commander. Both centralized and decentralized control/sensing/estimation schemes are possible, and dynamic ranges of interest for sensing/control are described. Key component/subsystem technologies are described which need both ground-based and in-orbit demonstration prior to their utilization in precision space interferometry missions using tethered formations.*

KEYWORDS: Tethered Spacecraft, Formation Flying, Dynamics, Control, Pointing, Retargeting

INTRODUCTION

NASA's future Earth and Space science missions involve formation flying of multiple coordinated spacecraft. Several space science missions (e.g., Terrestrial Planet Finder, Terrestrial Planet Imager, ST-3, LISA) include distributed instruments and a large phased array of lightweight reflectors and antennas, and long variable baseline space interferometers. A collection of collectors and combiner/integrator spacecraft will form a variable-baseline optical space interferometer for a variety of science applications. Formation flying spacecraft must conform to extremely stringent control and knowledge requirements. Precision requirements of such magnitudes have never existed before. The control system for space interferometry, for example, must provide precision station-keeping from coarse requirements (relative position control of any two spacecraft to less than 1 cm, and relative attitude control of 1 arcmin over a large range of separation from a few meters to tens of kilometers) to fine requirements (nanometer relative position control, and .01 milliarcsec relative attitude control).

Achieving the needed precision alignment, maneuvering, and synchronized motion of a set of spacecraft is a real challenge that we must face in the envisioned formation flying missions. Conformance to such precise performance metrics presents new challenges, not only in the areas of guidance, estimation, and control, but also in the areas of dynamic modeling of the formation flying spacecraft and its environment. Future Space and Earth Science missions involving space interferometers have been proposed which involve primarily three different types of spacecraft.

In the first type of space interferometer, a large, monolithic truss-based spacecraft supports the optical interferometric instrumentation and spacecraft bus within the same vehicle. The variable baseline of the interferometer is obtained by translating light collectors relative to one another along tracks to provide coarse baseline control, while fine control stages involving fast steering mirrors, voice coils, and piezoelectric stacks remove residual errors and allow the system to reach the needed optical quality for the synthesized image. The need to have high resolution translates into the necessity of constructing a large track (10 meters in the Space Interferometer Mission), and therefore, because of mass and stiffness limitations, very large interferometers are precluded in this construction.

In the second type of space interferometers, separated spacecraft acting as light collectors and combiners fly in formation, and therefore very large baselines are possible. Examples of formation flying interferometric spacecraft are StarLight and TPF (Terrestrial Planet Finder) [1]. By accurately controlling the separation and relative angle between the individual spacecraft more or less autonomously, interferometric accuracy may be obtained for maintaining the instrument's baseline. The process of controlling the interferometer baseline usually occurs in two stages: a coarse control stage relies on on-board formation attitude control systems to drive the relative range and bearing to specified values, and a fine control stage relies on driving the optical elements on board the collector/combiner spacecraft to satisfy the nanometer level relative position requirements requirements during observations. In this way, it is possible to reconfigure the entire formation to a new baseline over an enormous dynamic range imposed by kilometric distances and rapid dynamic changes.

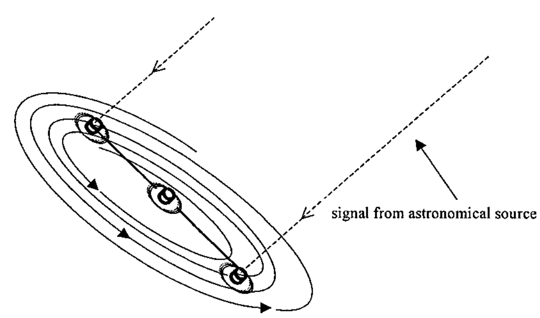


Figure 1. Tethered Interferometer Operation during Source Observation

In the third type of space interferometers, apertures of kilometric size are realized by connecting two or more light collecting spacecraft by means of one or more tethers. The advantage of using the tethers is that ([2], [3]) a variable controllable baseline can be achieved by reeling the tethers in or out, with a much smaller fuel consumption for reconfiguring the spacecraft as compared to the case of separated spacecraft in formation, in which on-board thrusting is continuously required.

The presence of an extremely lightweight structural connection between spacecraft allows a degree of independence of the spacecraft, but at the same time constitutes a reconfigurable, large space structure capable of pointing and maneuvering as a unit. Depending of the envisioned application, different precision requirements exist: they are more stringent for space science applications such as interferometric observations or the realization of large two-dimensional sensor arrays, and less stringent for Earth science applications such as sensor webs that respond effectively to events within the Earth system or for enabling human operation and exploration in space [4].

The idea of connecting the spacecraft to each other by means of a lightweight deployable tether is particularly attractive because: a variable baseline for interferometric observations can be achieved by deploying or retracting the tether; the coverage of the observation plane can be done continuously by spinning the whole system; the high levels of propellant consumption currently demanded by the ACS (Attitude Control System) of separated spacecraft in formation can be dramatically reduced by clever tension control of the interconnecting tethers; and two-dimensional and three-dimensional architectures can be constructed. Figure 1 depicts a configuration of a tethered interferometer in heliocentric orbit currently being considered by a joint JPL-S.A.O. research study ([3], [6]).

The nature of a tethered formation is such that both a gravity-gradient stabilized, an aerodynamically stabilized, and an electrodynamically stabilized attitude can be achieved in LEO. In the case of the tethered formation depicted in Figure 1, a very stable tethered configuration, i.e. with minimal retargeting, can be maintained during several orbits of virtually any inclination. However, to mitigate the thermal dynamics ensuing in the system at each terminator crossing, a polar sun-synchronous orbit would be preferred. Additional off-the-shelf ACS and tether deployer technology could be used at a relatively low cost. This would make a LEO demonstrator of a tethered formation for space interferometry possible in the near term.

In this paper, first, we describe the drivers and constraints for tethered formations designed for space interferometry, and explain why tethered formations can play a major role in space interferometry. Next, we discuss the approach to predicting the performance using dynamics models and control, sensor and estimation models required by a tethered system. Next, we identify the key sensing/control authority levels which space interferometry demands of tethered formations, and outline a roadmap for ground testing and in-orbit testing of key tethered formation component technology. Finally, we mention the progress in "smart" tether concepts recently being explored at JPL

DRIVERS AND CONSTRAINTS OF TETHERED FORMATIONS

There are several potential drivers and constraints that affect a tethered interferometer system design [3]:

- *pointing stability:* The pointing direction of the interferometer is required to be held within one arcminute (at 1 km baseline) with respect to the line of sight throughout the period of an observation.
- *distance collectors-combiner:* The distances collector1-combiner and collector2-combiner must never differ more than 10 cm from each other.
- *minimum tether tension:* For a tether to be controlled at the cm level a minimum tension of about 100mN is required so that inner residual tensions and hysteresis phenomena can be limited. Moreover a higher tension is an asset for the stability of the interferometer subjected to solar pressure.
- *maximum tether tension:* Depending on the diameter of the tether the tension should be at least one order of magnitude less than the material yield tension, based on current structural margins used in design.

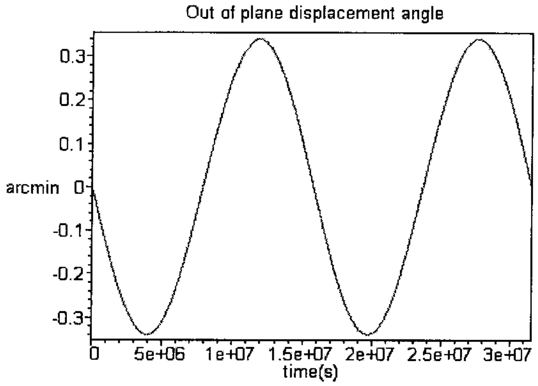
- *maximum tangential velocity:* The minimum number of photons of the observed source to be collected at a certain baseline length and orientation provides a limit for the maximum tangential velocity of the end mirrors. This velocity should be of the order of 1-5 m/s, provided that sufficiently large mirrors and advanced photon detection systems are employed.
- *Boresight with respect to the Sun:* The angle between the anti-Sun direction and the boresight axis must be kept under 20-30 degrees to prevent the solar radiation noise from degrading the measurement.
- *u,v plane coverage:* The Fourier plane would need to be fully sampled from ideally zero to 1000m baseline and as rapidly as possible (i.e. not longer than 3 days). The high-resolution area (from 100 to 1000 m baseline) is scientifically the most important.
- *fuel consumption:* The thrusting maneuvers should be reduced as much as possible. The ideal solution would be to keep the magnitude of the angular momentum constant throughout the entire observing mission and be able to fulfill all the requirements.
- *survivability:* The tether has to be able to survive in a micrometeoroids environment with high probability (more than 95%) for a 4-5 years mission.

The tether spacecraft capabilities we need to validate in flight are technologies which enable variable baseline control (deployment, retrieval sensing and control), active damping of tether longitudinal modes via a tether attachment point dynamics, stability of the configuration during observations, and minimization of orbital dynamics effects by proper selection of the orbit. Other goals we would like to demonstrate are uniform deployability, and to assess the feasibility of covering the interferometric UV plane with required precision when elasticity of the tethers (lag) is involved.

WHY TETHERED FORMATIONS CAN PLAY A MAJOR ROLE IN SPACE INTERFEROMETRY

The building block of the formation is a tether connecting two (or more) telescopes on a line. Our teams at SAO and JPL have analyzed in details the orbital perturbations acting on a linear formation in heliocentric (Earth trailing) orbit and the resulting dynamics for the last one year [9]. The conclusions of our study are that the contributions of disturbances associated with the tether dynamics forced by external perturbations to the overall pointing and relative positioning of the formation are negligible when compared to the effect of the same perturbations acting on the satellites. A steady-state pointing (of less than 1 arcmin) and positioning requirements (of less than 1 cm) specified for the free-flying formations can be met by a tethered configuration in heliocentric orbit. Figure 2 shows the pointing angular errors of a 1-km-baseline tethered system formed by two collectors and a central combiner on a line. This figure was derived for a specific initial orientation that drives the out-of-plane hard but not the in-plane. For other initial orientations, the in-plane angle is more perturbed than the out of plane but the overall pointing errors of the tethered interferometer in heliocentric orbit are always below 1 arcmin over periods of many months without requiring any overall attitude formation control during the observations.

A comparative analysis of the perturbations acting on the satellite vs. those associated with the tether itself indicates that the satellite sun shields contribute 99% of the relevant environmental perturbation forces while the tether only contributes 1%. In conclusions, the contribution of the tether to the formation errors is negligible when compared to the effect of the perturbations acting on the satellites sun shields. Geometric and/or optical asymmetries of the sun shields will produce the lion share of the differential-mode noise components that will impact the control of the free-flying formation. The tethered configuration is actually more robust than the free-flying formation at tolerating those effects because thanks to the higher spin rates, it has a higher angular momentum and greater stability.



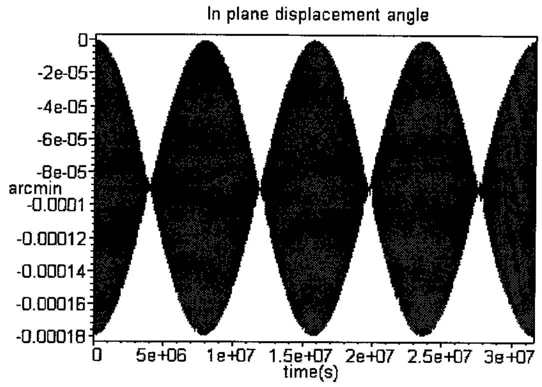


Figure 1 Pointing angular errors of tethered interferometer in solar orbit (over 1 year). Baseline length = 1km; rotation period = 2 hr 20 min; symmetric sun shields on collectors

Another important point is that besides being negligible the noise brought about by environmental perturbations acting on the tether is a common-mode type of noise, that is, it alters equally the optical path lengths of the interferometer and consequently it does not require differential corrections of the optical path lengths. Differential-mode noise can be produced by retargeting maneuvers that excite odd modes of lateral tether vibrations. The amplitudes of these modes are proportional to the retargeting speed and are strongly limited by the tether tension. Retargeting maneuvers of the tethered interferometer and techniques for damping out those modes will be one the subject of our future research. Finally, the spectral content of a tether for TPF in the length range 100 m to 1 km is at low frequency. Natural longitudinal (i.e., stretching) modes are readily damped out by material damping or simple tether attachment damping devices and they are not a concern. Natural lateral modes have first-harmonic frequencies in the range 0.1 Hz to 0.03 Hz assuming a 1-hr rotation period as a reference. The frequency of the satellite attitude oscillation due to the tether tension is in the range 0.0003 Hz to 0.001 Hz. The frequency of external perturbations acting on the tether are also very low, appearing at one or twice the rotation frequency and orbital frequency. This low frequency content points to the fact that the decreasing-amplitude higher-order harmonics should not be a problem for the fine control system of the TPF delay lines which is designed for a 1 kHz frequency range.

Consider an interferometer configuration in which the four in-line collectors of TPF could be connected by a light (a few kilograms) tether with a relatively simple mechanization while leaving the combiner free flying. In this case a very large portion of propellant can be saved for station-keeping the four collectors during observations (only the combiner needs to be propelled) and for aligning the bearings of the collectors with respect to one another. It is easy to estimate from the geometry of TPF that the propellant for station keeping can be reduced by a factor of 6.7 in a tethered collector formation with respect to the free-flying configuration. Because of the lower propellant consumption, the spin rate of TPF could be increased from the present 8 hours to, let us say, 2 hours or even 1 hour (as indicated in [1]) by enabling the observation of a larger set of target stars for planets search. Figure 3 shows the propellant required exclusively for planets detection for the free-flying TPF and the four-tethered-collector configuration. Planet detection (for which propellant estimates are available from the TPF study [4]) accounts only for a portion of the total propellant expenditure of TPF. Imaging astrophysical sources which requires continuous covering the u-v plane can also be readily accomplished in a tethered formation. The tether simply remove the limitations imposed on TPF by the propellant consumption which limit the observation spin rate (that is the number of targets) and builds more flexibility into the mission operation by adding a propellant-free actuation capability for baseline reconfiguration and u-v plane coverage.

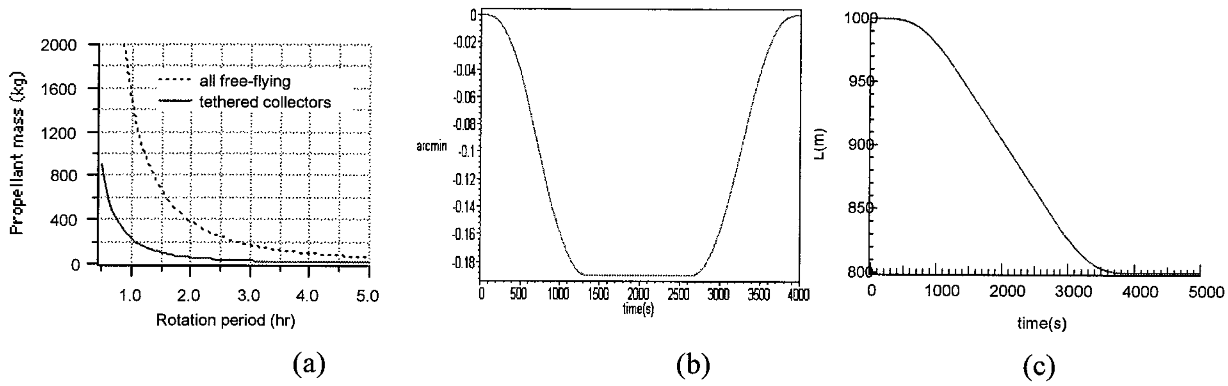


Figure 4 (a) cumulative propellant (adapted from Ref. [1] required for planet detection for a TPF with all free flying elements and a TPF with four tethered collectors ; (b) bearing angular error during a reconfiguration maneuver with (c) baseline length varying from 1000 m to 800 m.

Reconfiguring the baseline from one length to another can also be accomplished by reeling in (or out) the tether with the use of energy and no propellant. Figure 3 shows the results of a simulation of a baseline reconfiguration from 1000 m to 800 m and the associated bearing angle error (produced by Coriolis forces) of one collector with respect to another.

In conclusions, the results of our analysis for a tethered formation in heliocentric orbit indicates that the steady-state dynamics of the tether forced by the environmental perturbations is small and its effect on the pointing and separation of the formation is well within the specified requirements. Moreover, tether dynamics produce low-frequency noise that should be handled readily by the broad-banded fine control system of TPF.

SYSTEM ARCHITECTURE

Figure 5 shows a conceptual description of the essential dynamic and control building blocks of the tethered formation simulation. It is composed of the formation guidance, the formation commander, the dynamics subsystem, the control and estimation subsystem, and the sensor subsystem.

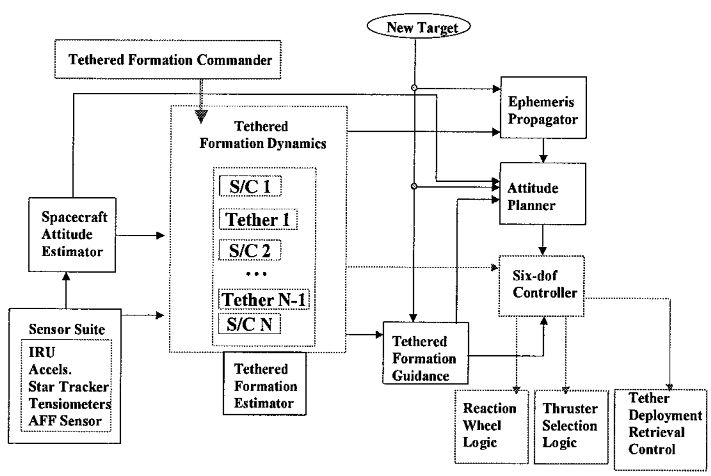


Figure 5. Essential dynamics and control architecture of tethered formation interferometer.

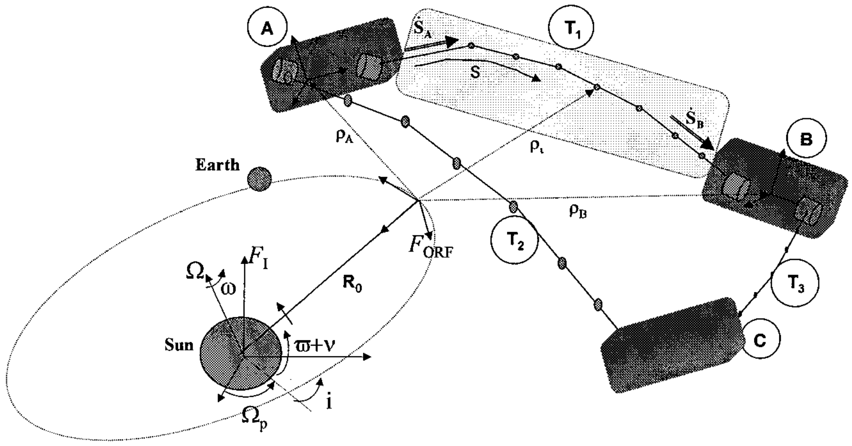


Figure 6. Precision Tethered Formation Dynamics Simulation Model.

Modeling and Dynamics

The conception of models and the design of simulation techniques for formation flying spacecraft poses significant challenges compared to those of conventional spacecraft. Since a formation can be defined as a spacecraft composed of physically disconnected vehicles, this fact only leads to an uncommon way to analytically represent its dynamics. The derivation of reduced order models for control, and the need to conveniently represent external perturbations and modeling uncertainties entering the model of a formation, also represent problems still unsolved. From a dynamical standpoint, a formation of spacecraft is characterized by a wide dynamic range (from less than 1 Hz in the spacecraft dynamics to KHz in the operation of the instrument synthesized by the formation), and by spatial scales ranging from sub-micron to kilometers. Techniques to model such wideband systems do not yet exist. The formation can be thought of a *virtual truss* ([5], [7]) in which the stiffness and dissipation levels of the connecting links are dictated by the control action on the relative sensing and actuation between two or more neighboring spacecraft. The dynamic model of this virtual truss suffers from undesired deformation modes caused by sensor noise, actuator non-linearity, dynamic uncertainties, and environmental disturbances.

In the following we describe some features of the model (see Figure 6) currently implemented in our simulation code [6]. The model covers both LEO and deep space scenarios. The simulation is hybrid in the sense that it is in part continuous (dynamics, commander), in part discrete (controller, sensing and estimation). The final objective of our modeling effort is to provide a simulation environment with the following capabilities:

- Orbital/Thermoelastodynamic analysis of a system of N spacecraft connected by one or more three-dimensional tethers.
- Realistic orbital parameters representative of LEO or heliocentric orbit. A zooming orbital reference frame approach, in which the local dynamics of the tethered system is referenced to a point which tracks the reference orbital motion. This approach splits the dynamics in orbital with respect to inertial, and in local with respect to orbital.
- Viscoelastic tether. Longitudinal oscillations are controlled by a critically tuned damper. Thermal tether dynamics is also present.
- Tether dynamics represented by a finite number of lumped masses capable of large displacements. Variable tether length, commanded by varying the tether deployment and

- retraction rates at the end of each tether segment (assumes a point mass reel located on each spacecraft at the end of each tether).
- Non-spherical gravity field (J0 and J2 harmonics of gravitational potential). Thermal perturbations (Sun thermal/radiation input, Earth's infrared radiation, albedo). Cooling by emitted radiation only. Dynamic atmospheric model (Jacchia 1977 model: diurnal variations linked to solar activity, seasonal-latitudinal variations, up to a height of 1000 km; nonrotating model).
- Attitude dynamics of each spacecraft with full actuation capabilities: Proportional Thruster-Based Reaction Control System and Reaction Wheel Based Pointing Control System.
- Global Formation Commander representing a centralized controller which commands the position and attitude of each spacecraft within the formation to follow a specific reconfiguration pattern. This reconfiguration is accomplished by varying the tether length and by spin modulation.
- Each spacecraft is equipped with a realistic sensor suite composed of IRU (Inertial reference Unit with accelerometers), Gyros, Star Tracker, AFF (Autonomous Formation Flying Sensor), and tether tension and length/length rate sensor. A Tethered Formation Estimator is located on-board each spacecraft which receives true dynamic sensor data and estimates real sensor data assuming user-defined sensor noise models.

Sensing/Estimation

Figure 7 depicts various sensing/estimation schemes required by tethered formations. Formation Estimation plays a key role in formation flying control of distributed spacecraft. The formation state estimator must provide estimates of the full state of the formation. Each spacecraft in the formation typically carries, among other sensors, a sensor which provides an estimate of the relative position between itself and other spacecraft in the formation (using optical metrology such laser-ranging, radiofrequency metrology such as AFF, etc). In order to fully appreciate the complexity of the formation estimation problem, consider the illustration in Figure 4, which depicts four possible architectures for information exchange for a formation of four spacecraft. The arrows denote the relative state measurement made by the spacecraft located at the tip of the arrow. For the simplest case (A) each member of the formation uses only the relative state with respect to a designated master. In the second case (B), a centralized solution is the only possible architecture. Architecture (C) allows any member of the formation to make, visibility permitting, relative state measurements with respect to any other member. In architecture (D) the master and another member of the formation, labeled Reference, form a "baseline". The Reference receives information only from the Master, while all other spacecraft in the formation use relative states with respect to the Master and the Reference. Lastly, the information could flow according to a certain pre-assigned ranking such as physical observabilities, measurement or observation sensitivities, maneuverability, and measurement covariances. A particular mechanization of information exchange will directly impact the quality of the formation estimate and therefore the quality of formation control. The problem of how best to do it is a complex one, even in the simple case illustrated here.

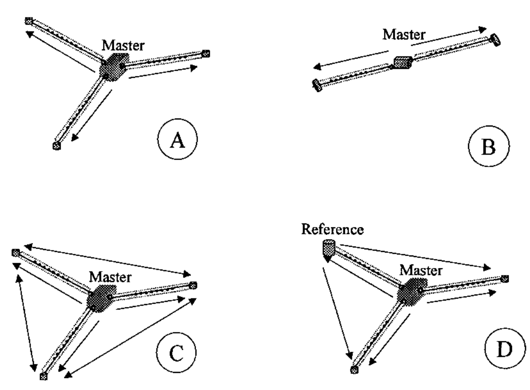


Figure 7. Four Possibilities of Making Relative State Measurements

After measurement and estimation, the following input data is available to the Commander/Controller of a tethered formation. For each spacecraft, we have: linear position, velocity, acceleration vectors, quaternion, angular velocity, angular acceleration vectors in relative bearing and bearing rate, relative range and range rate, all measured with respect to the vehicle's body frame, the neighbor spacecraft body frame, and the inertial frame. Available variables at each tether feed-out point are: tether length, length rate, length acceleration, tether tension, tether material strain and strain rate (thermal and mechanical). Available spin variables are: in-plane angle and rate, out-of-plane angle and rate, and current orientation of spin plane. The estimation of the attitude of each spacecraft is decentralized. Star tracker and gyro measurements are each spacecraft are processed to give the spacecraft attitude relative to an inertial frame. Accelerometer and relative position measurements in the form of an AFF sensor are also available.

Commander/Controller

We only consider the dynamics of the collector(s) relative to the combiner. We call this regime internal dynamics, which is different that the external dynamics mode in which the whole spacecraft receives commands aimed at changing its orbital dynamics (navigation-dependent mode). The proportional thrusters are of three different types: coarse (20N), fine (2N), and super-fine (mN level). The coarse RCS is used for retargeting and spin modulation. The fine RCS is used for attitude maneuvering and wheel desaturation, and the super-fine RCS is used for baseline modulation. The reaction wheel dynamic model contains viscous drag torque, ripple torque, and back emf motor torque. In addition, the reaction wheels are a source of noise, as it is assumed that wheel-specific imbalance forces and torques (modeled as wheel-rate dependent time series) act at the mounting location. This imbalance model type is empirical, where wheel disturbances consist of discrete harmonics of reaction wheel speed with amplitudes proportional to square of wheel speed. The observation cycle is at least of two types: Stop and Stare observing mode (in which the configuration is brought to a halt with zero relative velocity between spacecraft before any observations are attempted), and Observe on the Fly mode (in which fringe measurements on astronomical targets can be made while the spacecraft are moving). There are at least four internal dynamics control modes in the system when working as an interferometer [6]:

Attitude Rigidity Control Mode. This mode is used for fine pointing and stabilization only. It uses the Reaction Wheel Assembly located on each spacecraft, and uses local attitude and angular rate measurements on board each spacecraft, as well as information from the relative Attitude Estimator to ensure that bearing and bearing rate is within the specifications of the interferometer instrument (arcminute level or less).

Spin/Despin Control Mode. This mode is used to modulate the rotational spin rate of the system about its center of mass. This mode involves coarse level thrusters (20N level or above) firing tangentially (orthogonal to the spin vector) and depends on a precise estimate of the in-plane and out-of-plane angles between the line connecting two end spacecraft and the spin plane (global attitude mesurements).

Tether Deployment/Retrieval Control Mode. This mode is used to change the baseline of the interferometer (in which case this is a coarse actuation device), or to control the baseline finely for corrections at the centimeter level or less. This mode involves a continuous operation of the tether reels and fine thrusters (0.9N to milliN level), and reliable operation of the Autonomous Formation Flying Estimator (for range and range-rate measurements) and Attitude Estimator on board each spacecraft.

Retargeting Mode. This mode is used when the tethers are retracted into the collector spacecraft, and the whole system is repointed to a different target before the whole sequence of u-v plane coverage begins for the new target. This mode involves a precession maneuver, which is accomplished by firing the external (coarse) thrusters of the collapsed spacecraft assembly and relies on precise attitude knowledge only. The formation control system is proposed to be a hybrid of both decentralized and centralized controllers [7].

The combination of the coarse controllers (decentralized controllers) and the fine controller (centralized formation controller), together with the optimal formation commander, is envisioned to be essential for allowing large-scale maneuvers as well as precision formation motion. It is envisioned that a single controller will not be able to appropriately accommodate large variations in spatial scales and control requirements. Figure 8 depicts the spiral path being covered by a spinning tethered interferometer in observing mode. With minimal supervision, very accurate performance can be expected in this mode of operation, especially in deep space (heliocentric, Earth-trailing orbit), where the levels of dynamics noise from the environment are extremely low.

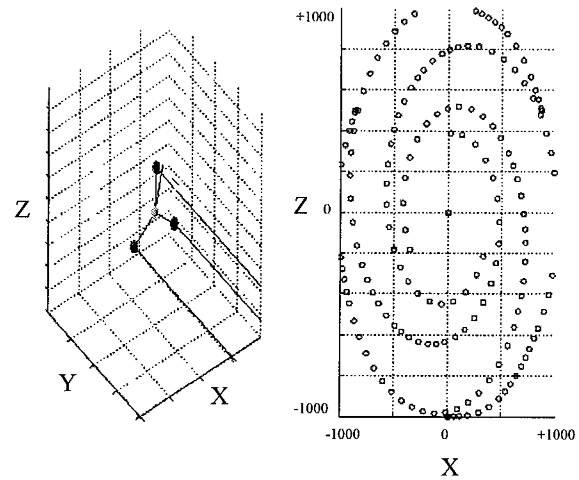


Figure 8. Spinning Tethered Interferometer covering a spiral path around the boresight.

SENSING/CONTROL AUTHORITY LEVELS FOR INTERFEROMETRY

Figure 9 depicts a block diagram of sensor and control levels for a tethered interferometer spacecraft with similar goals to the Terrestrial Planet Finder (imaging, nulling, planet finding). We may identify four levels of control and sensing authority with different bandwidths and precision:

1. Level 1: is the formation global control residing on the light-combining spacecraft. Ground communication links, inertial pointing, and inertial guidance for the formation are commanded from this location (0.1Hz, meters, arc-sec).
2. Level 2: refers to the control/sensing by each collector spacecraft for purposes of baseline stabilization (0.01-0.1 Hz, sub-cm and arcminute).
3. Level 3 refers to control authority enabled by RF and optical links to stabilize the metrology loop (KHz, micrometer, sub arc-sec).
4. Level 4 refers to tracking/nulling operations involving the maximum precision level of the interferometer during observation (KHz, nm and sub arc-sec).

The focus of the technology to be demonstrated in the LEO flight is on Level 1 and 2, although a demonstrator in deep space would be able to demonstrate Level 3 control and estimation technology.

TECHNOLOGY IN NEED OF DEVELOPMENT FOR FUTURE PRECISION TETHER APPLICATIONS

Several important technologies have already been demonstrated in-orbit during at least 16 tethered spacecraft flights:

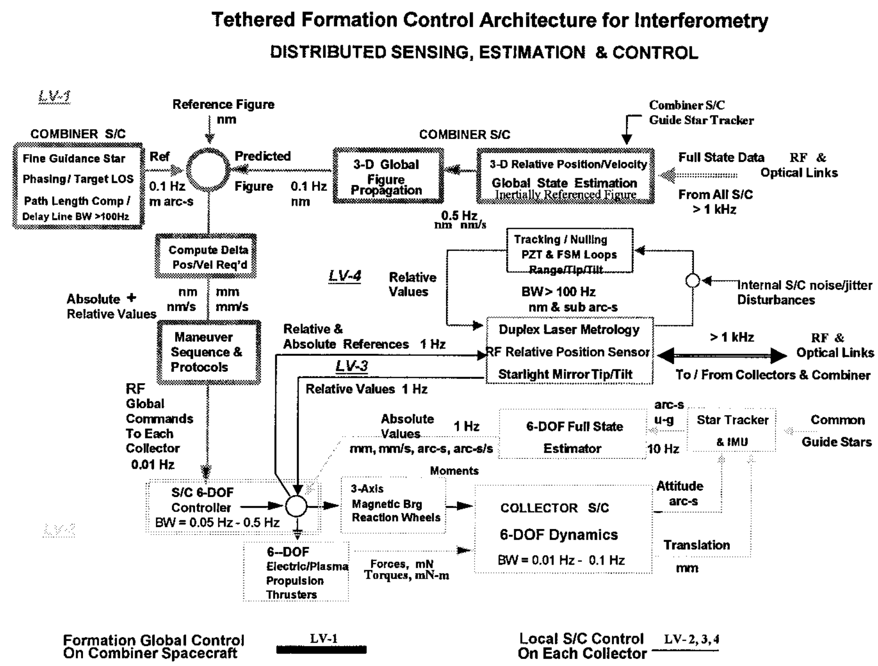


Figure 9. Sensing/Control authority for TPF class tethered interferometer spacecraft.

1. Controlled deployment, with accurate control along local vertical: +/- 10 degrees.
2. Controlled stationkeeping , allowing for long term orbit and attitude dynamic prediction.
3. Long-term (>5 years) survival and dynamic stability of a 4-km tether in LEO
4. Sizeable current flow in both directions (for boost and deboost applications) of conductive tethers.

Several technologies need further development before autonomous and reliable precision applications of tethered spacecraft can be made.

1. Controlled tethered system retargeting strategies to different sources in the sky.
2. Precision stationkeeping.
3. Disturbance rejection of tether dynamics.
4. Very smooth reeling in and out of tether suitable for precision baseline control.

These objectives can be accomplished with ground testing and in-orbit validation of the following key technologies:

1. Active control of tether attachment point, via movable hinge or movable boom;
2. passive control of tether attachment point, via dissipative flexures or joints;
3. autonomous on-board control logic for reliable deployment and retrieval at specified tether length and tension profiles;
4. space elevator technology, to enable distributed arrangements of tethered vehicles on a very long tether or multiple tethers;

5. accurate metrology between adjacent tethered vehicles (autonomous formation flying sensor in radiofrequency or optical mode) which does not suffer from scattered illumination from the intervening tether.

Ground Testing

The goals of ground testing are to verify the feasibility of key component technology to be used in a LEO demonstrator. The components of interest to be tested, as well as their relevance for space interferometry (in parenthesis) are:

1. Mechanization of tether attachment point. Control authority, precision and stability of operation (baseline stabilization and decoupling of tether dynamics from end spacecraft dynamics).
2. Optical (laser) metrology system between collector and combiner (optical metrology between collector and combiner).
3. Deployment and retrieval active control in autonomous mode (variable baseline control).

FURTHER DEVELOPMENTS IN SMART TETHER TECHNOLOGY

Figure 10 shows the approach being followed at JPL on developing advanced capabilities for a "smart" tether design. The idea [8] is based on implementing some ideas developed for tensegrity booms in order to conceive a tether that behaves as a controllable beam of extremely large aspect ratio. Each iteration of a topology optimization procedure produces a better design starting from a monolithic tether. Each iteration produces a design with higher stiffness, lower mass, and better utilization of the material in which some of the links are actively controlled. Finally, a global bending response can then be achieved for a member which, by definition, has no response in bending. Nonlinear tether behavior can be controlled in this manner. Additional properties such as micrometeoroid survivability, or reduced scattering properties in a selected band of the EM spectrum can also be included in the iterative procedure of topology optimization, thereby tailoring the mechanical/EM/thermal response of the tether to the bandwidth of interest. Further details are described in [8].

CONCLUSIONS

In this paper, we have described the models currently being used at JPL and S.A.O. for dynamics analysis, control, and estimation, of tethered formations in deep space and in LEO. The undergoing developments of the Formation Commander, Formation Controller, and Formation Estimator which will make possible the analysis and implementation of reconfiguration control schemes for very general configurations of Tethered\ Interferometers.

We have identified the features needed by a tethered interferometer in space in order to qualify as a system capable of imaging, nulling, and planet detection. The key technologies which need to be pursued and developed in order to achieve these goals have also been described.

Acknowledgments

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. E. C. Lorenzini was supported by JPL Contract 1215076. Thanks also to Dr. Fred Y. Hadaegh for providing support, and to Claudio Bombardelli for providing some results which have been used in the paper.

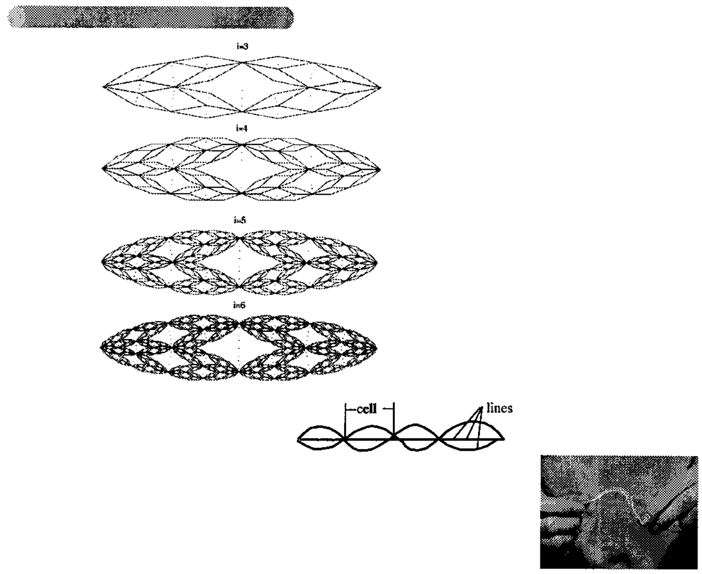


Figure 10. Conceptual development of a "smart" tether obtained by progressively following a topology optimization process.

REFERENCES

[1] *Terrestrial Planet Finder*, Beichman ,C.A., Wool, N.J., Lindensmith, C.A., eds., JPL Publication 99-3 (Jet Propulsion Laboratory: Pasadena, California, 1999).

[2] in *Proceedings of the Colloquium on Kilometric Optical Arrays in Space*, 23-25 October, 1984, Cargese, Corsica, France, European Space Agency.

[3] Bombardelli, C., Lorenzini, E., and Quadrelli, M.: *Pointing Dynamics of Tether-Controlled Formation Flying for Space Interferometry*, AAS paper 01-404, proc. AAS/AIAA Astrodynamics Specialist Conference, Quebec City, Canada, August 2001.

[4] Lorenzini E.C., *Novel Tether-connected Two-Dimensional Structures for Low Earth Orbit*. The Journal of the Astronautical Science, vol.40, #1, Jan.-March 1992.

[5] Hadaegh, F. Singh, G. Quadrelli M, and Shields, J.: *Modeling and Control of Formation Flying Spacecraft in Deep Space and Earth Orbits*, Terrestrial Planet Finder Technology Interchange Symposium, April 27, 2000.

[6] Quadrelli M.: *Modeling and Dynamics Analysis of Tethered Formations for Space Interferometry*, presented at the AAS/AIAA Spaceflight Mechanics Meeting, Santa Barbara, CA, February 11-14, 2001.

[7] Quadrelli M., Hadaegh, F.Y., Singh, G., and Shields, J.F.: *Some observations on the Dynamics and Control of Spacecraft Formations*, presented at the IFAC Conference on Aerospace Controls, Bologna, Italy, September 2-7, 2001.

[8] Quadrelli M., and Skelton, R.: *Smart Tethers for Distributed Spacecraft Applications*, in preparation.

[9] Lorenzini, E.C., M.L. Cosmo and C. Bombardelli, *Achieving Formation Stabilization an reconfiguration by Tethered Sapacecraft*, SAO Annual Report #1 under JPL Contract 1215076, September 2001.